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CFD modelling of a novel liquid Nitrogen/Air engine and cryogenic heat exchanger for small scale applications

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Abstract

Liquid nitrogen/air is considered as a promising energy storage vector where a number of mathematical and thermodynamic studies have shown its feasibility to provide cooling and power for both domestic and commercial applications. The current work presents a CFD modeling of storage system that uses liquid Nitrogen/Air generated using surplus electricity at off peak times or renewable energy sources, to provide cooling and power for domestic applications. Ansys Fluent 17.2 software was used in this study to model the main two components of the proposed system (cryogenic heat exchanger which provides cooling effect and expander (cryo-engine) that generates electrical power). The CFD modelling of boiling process of LN2 in the cryogenic heat exchanger was compared with an experimental data that available in the literature and showed a good agreement. Also, the model showed encouraging results where the engine power output reaches 2.2 kW at inlet pressure of 20 bar. Taking to account the generated cooling energy the total energy output reaches 14.6 kW which is enough to run domestic hoses at the peak times.

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Keywords: energy storage, cryogenic; Liquid air, Liquid Nitrogen, Boiling, Evaporating;

Nomenclature			
$coeff$	Coefficient	T_l	Liquid temperature
$\vec{F}$	Body force	T_{sat}	Saturated temperature
$\dot{m}_{lv}$	Rates of mass transfer due to evaporation and condensation, respectively	μ_m	The mixture viscosity
n	Number of phases	ρ	Density
v	Vapor phase	ρ_m	Mixture density
$V_{dr,k}$	Secondary phase drift velocity for phase k	ρ_v	Vapor density
$\overrightarrow{V_m}$	Mass-averaged velocity	α	Phase volume fraction
$\overrightarrow{V_v}$	Vapor phase velocity	α_k	Volume fraction of phase
		α_v	Vapor volume fraction
		β	Accommodation coefficient

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1. Introduction

Energy storage is considered the main solution of the mismatch between the electricity provider and the users demand leading to better network stability, energy saving, reduction in CO2 emissions. Curranty, liquid Nitrogen/Air (LN2/LAir), generated using surplus electricity at the off peak times or renewable energy sources is considered as the most attractive energy storage system due to its availability, high energy density and environmental friendly [1-3]. Mathematical models and thermodynamic analysis have been carried out by many researchers showing their potential and feasibility to provide cooling and power to meet various applications for both domestic and commercial buildings [4-6]. Some a prototype of LN2 engine was developed and fitted in a food transport truck to provide the required cooling [7, 8].
Key components in all reported systems for recovering the stored energy are the cryogenic heat exchanger used for cooling and the expander used for power generation. Therefore, the current work presents a CFD modeling of these two components where a concentric pipe heat exchanger that evaporates LN2 using a secondary coolant (Ethanol), and a cryogenic engine that uses the evaporated and superheated Nitrogen to produce power were modelled using Ansys Fluent 17.2 [9]. Modelling boiling process of LN2 was validated using An experimental data reported in the literature. A parametric study of the heat exchanger and the engine inlet conditions, and the engine optimum rotation speed were also investigated.

2. Liquid Nitrogen/Air cooling and power System

Figure 1 presents an overview diagram of LN2 energy storage system for generating cooling and power where renewable energy sources or off peak electricity used to run a liquefier plant for energy storage system for generating LN2 and storing it in a cryogenic tank at the saturated temperature and near atmospheric pressure to be used later on at the peak times. The storage temperature is very low near -200 °C which is low enough to run an engine between the ambient (around 20 °C) and the storage temperature. At the peak times where most electricity suppliers facing difficulties to meet the electricity demands LN2 is pumped to a heat exchanger (process 2 – 3) where it is evaporated and superheated (process 3 – 4) by the secondary coolant that circulates through the building to meet its cooling demands. The high pressure superheated gas then passes through an expander to generate power before it vents to the ambient (process 4 – 5).

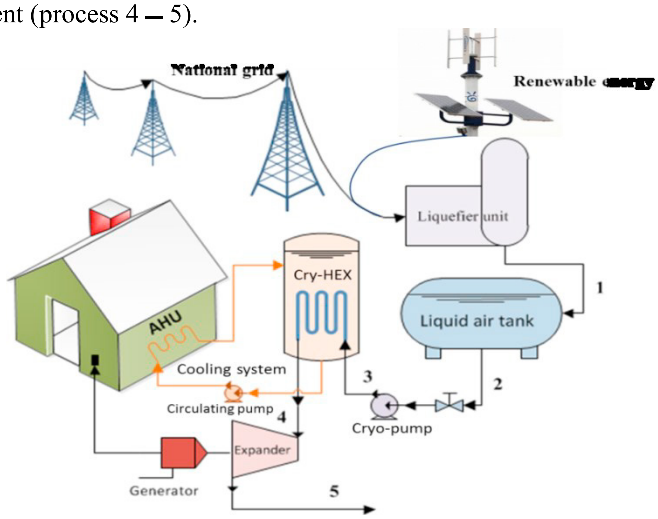

Figure 1 Liquid Nitrogen cooling and power System

3. CFD modeling

The proposed system provides two types of energy output; cooling by evaporating LN2 in the cryogenic heat exchanger and power by expanding the superheated gas in the expander. Enhancing these two components will lead to increasing the total power output. So the CFD model was only focusing on these two components.

3.1 CFD model of cryogenic heat exchanger

Figure 2 shows 2D schematic diagram of the concentric tube heat exchange where Liquid N2 enters to the tube side of the heat exchanger as liquid phase and leaves as superheated gas which means phase change (evaporating/boiling) is taken to account in this side while in the shell side the secondary coolant (Ethanol) enters at relatively high temperature and leaves at lower temperature. Figure 2 also show 3D meshed model of the heat exchanger using Ansys Fluent. For reducing the computational time only half of the heat exchanger was modeled as appears in the figure 2. In this model LN2 enters at 77K with various velocities and near atmospheric pressure while the Ethanol enters at 300K with various inlet velocities.
Regarding the model setup Mixture multiphase model was used, and it solves the energy, continuity and momentum equations for the mixture and the secondary phase volume fraction equation as following. In the model LN2 was defined as primary phase and N2 and Ethanol were set as secondary and third phases, respectively. The boundary conditions at the inlets were velocity inlet and at the outlets were pressure outlet and the LN2 entered at 77 K and Ethanol at 300 K.

- *Continuity equation*

$$\frac{\partial}{\partial t}(\rho_m) + \nabla.\left(\rho_m \overrightarrow{V_m}\right) = 0 \text{ .... (1)}$$

Where: $\overrightarrow{V_m} = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \overrightarrow{V_k}}{\rho_m}$ ....(2) and $\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k$ ....(3)

- *Momentum equation*

The Mixture model momentum equation cab obtained from the summation of the momentum equation of each phase individually as following:

$$\frac{\partial}{\partial t}\left(\rho_m \overrightarrow{V_m}\right) + \nabla.\left(\rho_m \left(\overrightarrow{V_m}\right)^2\right) = -\nabla p + \nabla.\left[\mu_m \left(\nabla\overrightarrow{V_m} + \nabla\overrightarrow{V_m}^T\right)\right] + \rho_m \vec{g} + \vec{F} + \nabla.\left[\sum_{k=1}^{n} \alpha_k \rho_k \left(\overrightarrow{V_{dr,k}}\right)^2\right] \text{ ....(4)}$$

Where:

$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k$ ....(5) and $\overrightarrow{V_{dr,k}} = \overrightarrow{V_k} - \overrightarrow{V_m}$ ....(6)

- *Energy equation*

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}(\alpha_k \rho_k E_k) + \nabla.\sum_{k=1}^{n}\left(\alpha_k \overrightarrow{V_k}(\rho_k E_k + p)\right) = \nabla.\left(k_{eff}\nabla T\right) + S_E \text{ ..... (7)}$$

$$E_k = h_k - \frac{p}{\rho_k} + \frac{v_k^2}{2} \text{ ..... (8)}$$

- *The Secondary Phases Volume Fraction Equation*

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla.(\alpha_p \rho_p \overrightarrow{V_k}) = -\nabla.(\alpha_p \rho_p \overrightarrow{V_{dr,p}}) + \sum_{q=1}^{n}(\dot{m}_{qp} - \dot{m}_{pq}) \text{ ..... (9)}$$

- *Mass Transfer Model*

The LN2 mass transfer equation has taken to the account in the Mixture Model where the Evaporation and Condensation model enabled. The model uses Lee Model (approach) and the equation as following.

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla.(\alpha_v \rho_v \overrightarrow{V_v}) = \dot{m}_{lv} - \dot{m}_{vl} \text{ ..... (10)}$$

$$\dot{m}_{lv} = coeff * \alpha_l \rho_l \frac{(T_l - T_{sat})}{T_{sat}} \text{ ..... (11)}$$

$$coeff = \frac{6}{d_b}\beta\sqrt{\frac{M}{2\pi R T_{sat}}}L\left(\frac{\alpha_v \rho_v}{\alpha_l - \rho_v}\right) \text{ ..... (12)}$$

3.2 CFD model of cryo-engine

The proposed system is an open system (consuming system) which means the LN2 will not be circulated so as reported in the literature increasing the expander inlet pressure leads to reduce the LN2 consumption, however, reducing the mass flow rate will add difficulty to the possibility of using a turbine as an expander.
In this study a novel reciprocating engine driven by high pressure and superheated N2 engine is presented and modeled. Figure 3 shows the engine components (50 mm piston at the Top Dead Center TDC, 50 mm cylinder,

intake valve and exit valve). The engine work with two strokes: power stroke and exhaust stroke. The first one starts when the piston at the TDC and the intake valve starts open and will close after 1/16 of the total cycle time. The high pressure air will push piston down to expand and generate power. Then at a time of 0.5/16 of the total cycle time before the piston reaches the Bottom Dead center BDC the exit valve starts opining to avoid any compression may happen in the second stroke (exhaust stroke). In this stroke the exist valve will remains open until the piston reaches the TDC again and this will add an advantage to this engine where no compression process that gives negative work will happen in the engine. A specific UDF was written using C programming language to simulate these two strokes with their piston movement and valve timing.

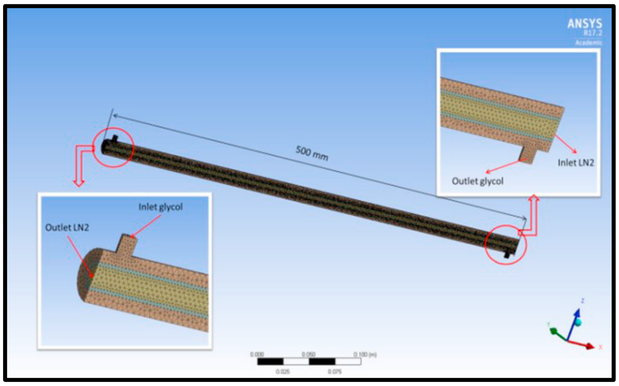

Figure 2 Cryogenic heat exchanger

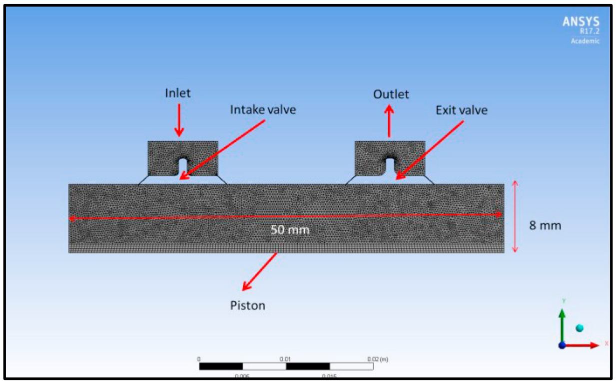

Figure 3 Cryogenic engine

4. Results and discussion

Figure 4 shows the test section used by H. Hu et al., 2012 who experimentally investigated the evaporation process of liquid Nitrogen in a vertical tube. This test section was modelled using the CFD method described above and the predicted temperature variation with time was compared to the experimental measurement showing good agreement with maximum deviation less than 14%.

Regarding the concentric cryogenic heat exchanger, the model consists of 210,000 mesh elements and was run using high performance computing system available at the University of Birmingham. The accuracy of the model was assessed using energy balance in terms of the energy rejected from the Ethanol side and the energy absorbed by the Nitrogen side being equal. Effect LN2 and Ethanol mass flow rates were investigated by changing their inlet velocities as shown in table 1.

Figure 5 (a) presents the outer surface temperature of the inner tube and it is clearly seen that, as the LN2 inlet velocity increases the wall temperature decreases and when the ethanol inlet temperature increases the wall temperature increases, while figure 5 (b) presents the heat exchanger temperature contours. The outlet temperature of the LN2 and the Ethanol sides presented in figures 6 (a, b) where they clearly show that, increasing the inlet velocity of LN2 decreases the outlet temperature while increasing the Ethanol inlet temperature increases the outlet temperature. However, the effect of the Ethanol inlet velocity on the LN2 outlet temperature is not significant after a certain value due to the limitation of the heat transfer in the Nitrogen side unless an enhancement has been made to increase the heat transfer area.

Regarding the cryogenic engine N2 was selected as working fluid and various inlet pressures (4, 6, 8, 10 and 20 bar) were investigated to find out their effect on the engine power output. Each of these inlet pressures has an optimum rotational speed that gives the maximum power output, for example, at inlet pressure 4 bar the rotational speed was 1500 rpm while at 10 bar was 3000 rpm. The inlet temperature was 300K and all walls assumed to be adiabatic where no heat can enter or leave the engine through them, however, the model showed rapid increasing of the temperature inside the cylinder to reach 400K in some areas due to rapid increasing of the pressure inside the cylinder as shown in figure 7. By assuming the initial position of the piston at the middle of the stroke, the changing of the pressure and temperature inside the cylinder with respect to the crack angle are presents in figure 8 (a and b). The figure indicates that, most of the time the engine temperature is less than the ambient so more likely to absorb heat from the surrounding leading to increase the power output which one of the advantage of this engine.

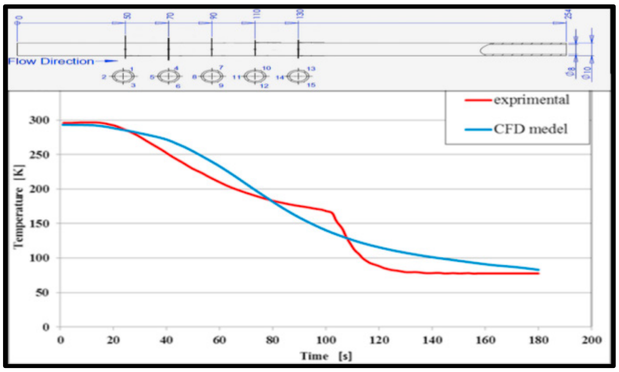

Figure 4 Compression between the experimental and CFD model

Table 1 Different cases for changing inlet velocities

Case No	LN2 inlet velocity [m/s]	Ethanol inlet velocity [m/s]
Case 1	0.1	0.1
Case 2	0.2	0.1
Case 3	0.3	0.1
Case 4	0.4	0.1
Case 5	0.1	0.2
Case 6	0.1	0.3
Case 7	0.1	0.4

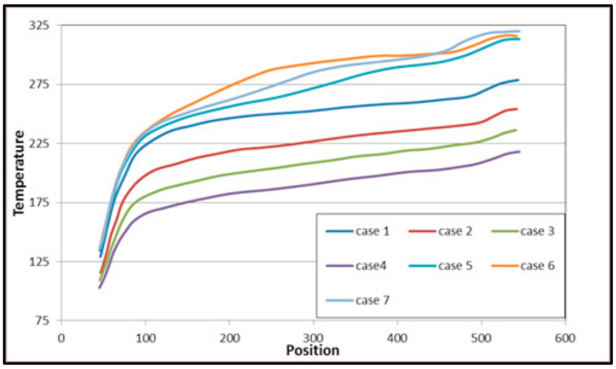

Figure 5 (a) inner tube surface temperature.

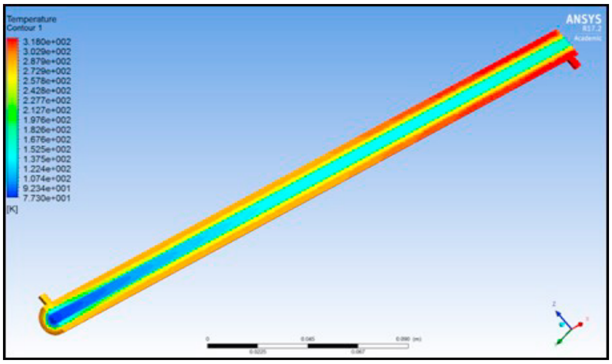

Figure 5 (b) the heat exchanger temperature contours

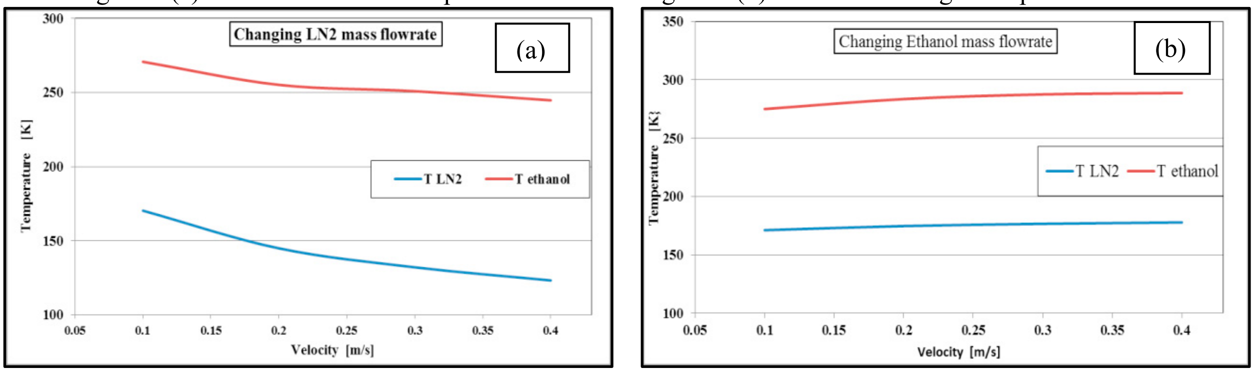

Figure 6. (a) Outlet temperature of the LN2, (b) Outlet temperature of Ethanol

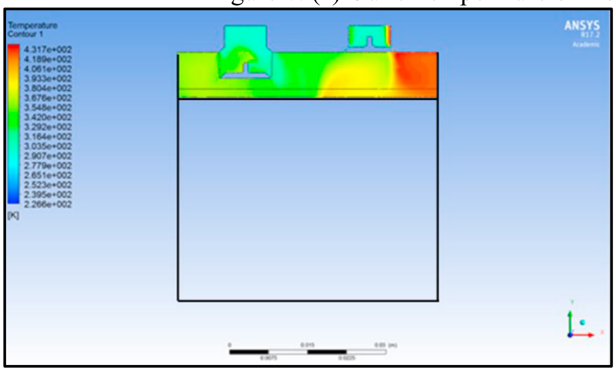

Figure 7 the engine temperature contours

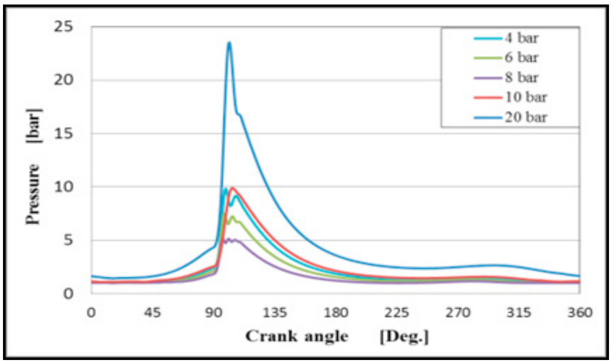

Figure 8 (a) pressure inside the engine vs. crack angle

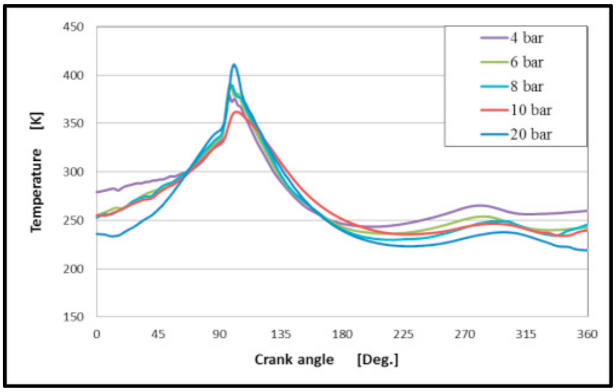

Figure 8 (b) changing temperature inside the engine vs crack angle

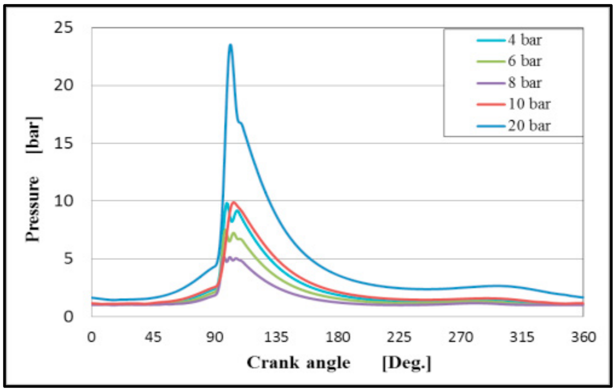

Figure 9. Engine PV curve

The engine power output was calculated by finding the area under the engine PV curve (figure 9) and multiplied it by its frequency. Table 2 is summarizing system output energies and mass flow rates of LN2 and Ethanol. The engine power output reaches 2.2 kW at inlet pressure only 20 bar with mass flow rate of 0.0239 kg/s and the total energy output reaches 14.65 kW when the cooling energy is considered.

Table 2 Summary of the LN2 and Ethanol mass flow rates and output energies

Inlet pressure [bar]	LN2 mass flow rate [kg/s]	Power [kW]	Ethanol mass flow rate [kg/s]	Cooling power [kW]	Total power [kW]
4	0.001789	0.160	0.022	0.927	1.087
6	0.003579	0.368	0.044	1.854	2.222
8	0.005968	0.641	0.074	3.092	3.733
10	0.008957	0.902	0.111	4.640	5.543
20	0.023942	2.245	0.297	12.405	14.650

5. Conclusions

The current work presents A CFD model of the main two components (cryogenic heat exchange and cryogenic engine) in the cryogenic systems that use the cold energy storage in form of liquid Nitrogen to provide cooling and power for domestic application during the peak times. The model was carried out using Ansys fluent 17.2. and it showed promising results, where at pressure inlet 20 bar, the total output power reaches 14.6 kW with very low LN2 mass flow rate of 0.024 kg-LN2/s which is enough to run domestic hose at the peak times. The current work also presents a validation of modelling boiling process of LN2 where a good agreement with an experimental data available in the literature was achieved with maximum deviation less than 14%. Further CFD modelling will follow in the future investigating higher ranges of inlet pressure and different heat exchanger configurations.

Acknowledgements

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